Effect on Discomfort of Frequency of Wrist Exertions Combined with Wrist Articulations and Forearm Rotation

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Abstract

This study investigated the combined effects of forearm rotation, radial/ulnar deviation and flexion/extension on discomfort score for two levels of frequency (10 and 20 exertions/minute) in a repetitive wrist flexion task with a force of 10N. There were three levels of wrist deviation (neutral, 35% ROM in radial and ulnar), three levels of wrist flexion/extension (neutral, 35% ROM in flexion and extension) and three levels of forearm rotation (neutral, 60% ROM in prone and supine). The dependent variable was discomfort on a Visual Analogue Scale. ANOVA results showed that there were highly significant effects of all the main factors ($p<0.001$) on discomfort. The two-way interaction of forearm rotation with radial/ulnar wrist deviation was highly significant ($p=0.001$) as was forearm rotation by participant. Similarly, three of the three-way interactions and one four-way interaction were high significant ($p<0.001$ and $p<0.01$), probably due to having participants as one of the factors in them. Posture changes from neutral to 35% ROM increased discomfort by about 20%, but combinations of deviated postures increased discomfort by up to 70%. The higher frequency increased discomfort by 28%. Some of the increase in discomfort appears to have been due to reductions in wrist flexion MVC at non-neutral postures.

Relevance to Industry

The results of the study will be beneficial for the design of work places, hand tools and task design in repetitive industrial manual work, for example, in assembly work requiring a light force and a frequency of about 10 to 20 exertions per minute.

Keywords: Wrist and forearm postures; musculoskeltal disorders; discomfort

1 Introduction

The dose–response relationships involved in the development of Work-related Musculo-Skeletal Disorders (WMSDs) are unknown, but the factors responsible for the development of discomfort are known (Putz-Anderson, 1988). The literature shows unarguably that certain jobs and certain work-related factors are associated with the manifold risk of contracting WMSDs compared with other population groups, or groups not exposed to these risk factors (Silverstein, 1985; Ayoub & Wittels, 1989; via. Hagberg, et al., 1995). Moore et al. (1991) and Tanaka & McGlothlin (1993) introduced the model that explains the aetiology of a type of WMSD, Carpal Tunnel Syndrome (CTS), by the frictional load inside the carpal tunnel and the tendon sheaths. This friction was assumed to be a product of three biomechanical factors: internal force, repetitiveness and wrist angles. Drury (1987) developed a method of measuring these factors and their effects on WMSDs and demonstrated its effectiveness in an industrial task. Putz-Anderson (1988) considered these factors, combined with duration and recovery characteristics, as the most important causes of WMSDs. But in-vivo experimentation using objective stress measurements are often complicated by ethical necessities to not engender injuries, so thus other measures of postural distress are needed.

Investigators have turned to the psychophysical approach using short-term responses to physical stress in experimental simulations of industrial tasks (Lin et al. 1997). The Visual Analogue Scale (VAS) has been shown to be a valid and reliable method to assess the intensity of discomfort (Hukisson, 1983). Hukisson stated that the VAS tool has advantages such as its sensitivity, simplicity, reproducibility, and universality e.g. independent of language. Discomfort is usually a precursor to pain and injury, and has been used to assess the adverse effects of various industrial tasks (Corlett and Bishop 1976). Genaidy and Karwowski (1993) studied joint discomfort for postural deviations at various joints of the body and devised distinct classes of joint deviations from neutral postures, which need to be assigned different weights of postural stress. More recently rating scales such as VAS have been used to estimate perceived pain/discomfort for a variety of repetitive occupational tasks (Genaidy and Karwowski 1993, Snook et. al. 1995, Lin et al. 1997, Aaras et. al. 2002, Carey and Gallwey 2002 and Labus, et al. 2003).

Lin et al. (1997) developed mathematical equations to predict discomfort score for wrist flexion at two different levels of frequency of exertion (4 & 20 motions/minute) and two forces (15N and 45N). Previous studies looked at the effects of individual postures, or combinations with other postures, of upper limbs on discomfort (Lin et al., 1997; Carey & Gallwey, 2005; and O'Sullivan & Gallwey 2005). But none appears to have investigated the issues of combining wrist posture with forearm rotation on discomfort. However Reeves and Young (2003) did indicate that interactions of wrist and forearm posture may play a critical role in identifying a causal relationship with Carpal Tunnel Syndrome (CTS) as well as describing the dose-response relationship between posture and CTS. Likewise Mogk and Kier (2003) investigated the effect of wrist flexion/extension and forearm rotation on forearm muscle loading during gripping but did not include wrist radial/ulnar deviation. They found that forearm rotation affected grip force generation only when the wrist was flexed, with force decreasing from supination to pronation ($p=0.005$).

Some experimental studies have used simulations of real tasks to develop mathematical models to portray relative changes in discomfort for combinations of wrist and forearm postures for a number of specific exertions (Carey & Gallwey, 2002; Carey & Gallwey, 2005; O'Sullivan & Gallwey, 2005; and Mukhopadhyay et al., 2007a). Carey & Gallwey

(2002) used a pronated forearm combined with wrist articulations of 35% and 55% of the ROM in each of the four quadrants of radial/ulnar and flexion/extension, with a downwards non-prehensile force and developed iso-discomfort contours for two levels of force and frequency. However, in most industrial jobs, the task force and frequency are fixed and so Carey & Gallwey (2005) developed a mathematical model for wrist discomfort levels for the same task with combined movements at a constant force of 10N +/- 1N and at a frequency of 15 times per minute. There were 49 combinations of flexion/extension and radial/ulnar deviation with the task performed for 5 min at each combination. Again iso-discomfort contours were developed to show the relative changes from neutral to extreme postures. However, in no part of either study by Carey and Gallwey, were the wrist postures combined with forearm rotation.

In contrast O'Sullivan & Gallwey (2005) examined discomfort for five-minute durations of intermittent isometric torque exertions at 20% MVC in pronation and supination at eleven forearm angles. They developed regression equations to depict relative discomfort as a function of forearm angle (in %ROM). Mukhopadhyay et al. (2007a) extended this work by combining forearm rotation with elbow angle and exertion frequency, at two levels of pronation torque. In all cases the wrist was at neutral in both flexion/extension and ulnar/radial deviation so the combined effect of wrist and forearm non-neutral postures was not examined. Khan et al. (2009a) extended upon other studies in the University to investigate the effects of combined wrist radial/ulnar deviation and forearm rotation on discomfort for a wrist flexion task. That study found highly significant effects for both wrist deviation and forearm rotation on discomfort, and discomfort equations were developed that predict these effects. In a subsequent experiment Khan et al. (2009b) studied the effects of wrist flexion/extension and forearm rotation for two levels of relative force (10 and 20% wrist flexion MVC) on discomfort. This research needs to be extended to study the effects of exertion frequencies combined with wrist deviation and forearm rotation on discomfort. Also, not all wrist and forearm combinations of postures involved in industrial work have been studied by these authors and this work needs further research.

The purpose of the present study was to study discomfort for intermittent isometric wrist flexion exertions, at various levels of prone/supine forearm rotation combined with wrist flexion/extension and wrist radial/ulnar deviation. The aim was to provide a basis for more extensive studies and to develop a model of discomfort in wrist flexion tasks, especially to show the manner in which the discomfort changes as the posture changes towards the extremes.

2. Method

2.1 Participants

Public calls were made on the university campus for volunteers and each was paid €42 for their participation. Approval was obtained from the Ethics Committee of the University before starting the experiment. There were twenty right-handed male participants with a mean age of 22.5 (SD 3.5), height 178.9cm (SD 6.7) and body mass 73.6kg (SD 10.6).

2.2 Postures

Initial trials demonstrated that 55% Range Of Motion (ROM) flexion/extension and 55% radial/ulnar deviations could not be combined with 60% ROM of forearm rotation, so these extremes were avoided. Hence there were three levels of wrist flexion/extension (neutral, 35% ROM in flexion and extension), three of radial/ulnar deviation (neutral, 35% ROM in radial and ulnar), and three levels of forearm rotation (neutral, 60% ROM in prone and supine). These posture descriptions are illustrated in Figure1.

2.3 Apparatus

A rig was designed to provide the wrist and forearm rotation with a fixed posture of the upper arm and forearm support (Figure 2). A force meter designed in-house was interfaced with a 333MHz Pentium processor based PC via an RS232 serial port. Penny & Giles electro-goniometers were also connected to the PC using a National Instruments board (PCI MIO 16XE-50) for data acquisition and experimental control. LabVIEW6i code was written to provide Virtual Instruments (VIs) (Figure 2) to monitor and control both the initial and main experiment (Figure 3 and 4 respectively).

[put Figure 1 about here]

[put Figure 2 about here]

[put Figure 3 about here]

[put Figure 4 about here]

Angular movements of the wrist and forearm were shown in real time on the screen. A vertical slider bar indicated the flexion force with bands labelled at ±1N about the level of 10N. To maintain good control of the task, a buzzer sounded and the vertical bar changed colour from green to red, if the participant's force exertion went outside the range. The screen clock displayed the duration of exertion corresponding to the frequency of 10 or 20 exertions per minute.

2.4 Initial Experiment

In the light of previous experience it was apparent that wrist flexion MVC would be different at the non-neutral postures and so an initial experiment was conducted to measure flexion MVC at each postural combination. A factorial design was used with three levels of wrist flexion/extension, three levels of wrist deviation, and three levels of the forearm rotation, as for the main experiment and following the same protocols. There were eight right-handed male participants with a mean age 26 (SD 2.56); height 177.1 cm (SD 8.2) and body mass 74.8 kg (SD 5.6).

2.5 Experimental Design

It was a full factorial design with three levels of the wrist flexion/extension, three levels of wrist radial/ulnar deviation and three levels of the forearm rotation, for two levels of frequency (10 and 20 exertions per minute). These correspond to the cut off limits for low and high receptiveness for hand wrist movements according to You and Kwon (2006). The treatments of the experiment were ordered in specific blocks because of the difficulty of adjusting three postural factors at the same time between each part of the experiment. Within one level of forearm rotation a sequence of the levels of wrist flexion/extension was selected. Similarly, for every level of wrist flexion/extension, an order of radial, neutral and ulnar deviation was selected for half of the participants. For the other half this order was reversed (ulnar, neutral and radial respectively). Within this, for each level of wrist deviation, the order of the frequency levels was 10 and 20 respectively for half of the participants, and the reverse for the other half. This ordering helped to limit annoyance to the participants and reduced the number of adjustments between treatments.

The repetitive task of Carey and Gallwey (2002) was used i.e. a 10N ± 1N isometric flexion force. The level of force used in this study was within the range of forces observed as characteristic of many light force repetitive industrial tasks e.g. meat cutting, assembly tasks and wire tying (Aaras et al., 1988, Li, 2002 and McGorry et al., 2002). There are probably many tasks where the forces may be higher and where these results may not be applicable.

2.6 Dependent Variable

Participants used the cursor to indicate their discomfort score on a 100mm Visual Analogue Scale (VAS) which was adjusted to a scale from 0 to 10 (Figure 4). Participants were advised that symptoms of discomfort included aching, fatigue, soreness, warmth, cramping, pulling, numbness, tenderness, pressing or pain (Lin et al., 1997).

2.7 Preliminary Data Collection

Initially the participant was briefed about the experiment and questions were answered before signing the informed consent form. Then the participant was seated in a fully adjustable chair.

2.7.1 Ranges of Motion (ROMs)

The Penny and Giles goniometers were fitted to the wrist and forearm in accordance with the manufacturer’s instructions. Then the elbow was flexed 90^0, the upper arm was placed close to the body (0^0 abduction), and the wrist was at neutral in both planes. Wrist deviation and flexion/extension ROMs were measured for the fully prone forearm, (Carey and Gallwey, 2002).

2.7.2 Wrist Flexion MVC

The forearm was fully prone with a neutral wrist, and the elbow was flexed at 90^0 inline with the postures for the experimental task of Carey & Gallwey (2002) and the same as the task chosen by Carey and Gallwey (1999). The participant's hand was positioned so that the distal metacarpophalangeal joint of the third phalange was over the centre of the force gauge. A Velcro strap held the forearm on the table to prevent movement during the experiment. As per the experimental order the rig was adjusted and the participant was asked to exert the maximum wrist flexion force twice with a gap of 2 minutes, the maximum of these being recorded as the MVC for that particular posture. After obtaining each MVC score a gap of 2-minutes was allowed before starting measurement of the next one.

2.7.3 Endurance Time

Endurance time at 50% MVC was recorded to use as a covariate to control for differences in discomfort perception and pain tolerance. The endurance test was also used to train the participants in the interpretation of the discomfort scale anchors. A five-point VAS display with indicators of "No discomfort", "Medium discomfort", and "Extreme discomfort", (as per Corlett and Manenica, 1980 and the main experiment) was presented to the participants . During the endurance test they informed the experimenter when their perceived discomfort reached each of the levels. A special LabVIEW Virtual Interface controlled this part, as shown in Figure 5.

(put Figure 5 about here)

2.8 Procedure

The participant and rig were positioned at the same settings as for the preliminary data collection for wrist flexion MVC, except for fixing the forearm and upper arm on the rig so that the elbow was flexed at 90^0, the forearm was horizontal, and the upper arm was at approximately 45^0 in the coronal plane. A Velcro strap held the forearm on the table to prevent movement during the experiment. The wrist force exertion was maintained for the last second of the clock cycle shown on the screen shot of LABVIEW 6i VI (Figure 4). At the end of each five-minute block, the participant rated discomfort on the 100mm VAS and rested for at least one minute, or until the participant felt no discomfort, to obviate cumulative fatigue (Carey & Gallwey, 2002). After approximately half of the experiment, a rest of about 30 minutes was given. The whole experiment took about 8 hours for each participant.

2.9 Results analysis

All statistical analysis was performed using SPSS software. Full factorial design was used for univariate repeated measures Analysis of Co-Variance (ANCOVA). This technique was used to investigate the expected significances of covariates (endurance time and flexion MVC), independent variables (forearm rotation, flexion/extension, wrist deviation and frequency) on the dependent variable (i.e. discomfort score: transformed as it was required). Further post hoc tests were used to test the significance of the different levels of independent variables.

To reduce the effect of differences in pain tolerances among participants, and to enable comparisons with the data of previous studies, the data were standardised using the min-max procedure of Gescheider (1985) to give Standardised Discomfort Score (SDS) values, as follows,

$$\text{Standardised Discomfort Score (SDS)}_{ij} = \frac{(\text{raw data}_{ij}-\text{min. data}_{j})}{} \times 10$$

$$(\text{max. data}_j - \text{min. data}_j)$$

Where, raw data_{ij}: discomfort score for i^{th} treatment for j^{th} participant
min data_j: minimum discomfort value within data of the j^{th} participant
max data_j maximum discomfort value within data of the j^{th} participant

3. Results

3.1 Initial Experiment on Wrist Flexion MVC

These data are presented in Table 1. Levene's test for non-normality was rejected (p=0.992) and an ANOVA was performed on the MVC data with Participants as a random factor. The results showed that forearm rotation and participants were highly significant (p=0.001) while wrist flexion/extension was significant (p=0.018). But wrist radial/ulnar deviation was not significant (p=0.053). All interaction effects were not significant except for wrist deviation with participant (p=0.003) and the three-way interaction of forearm rotation with wrist flexion/extension and participant (p<0.001).

The greatest decrease in the flexion MVC was 35.8% for the extreme combination of 60% ROM prone with 35%ROM wrist flexion and 35% wrist radial deviation. The mean value of the wrist flexion MVC for the neutral wrist and forearm was 83.8 N (SD 33.26).

[put Table 1 about here]

3.2 Main Experiment Wrist Flexion MVC and Endurance time

Mean flexion MVC across the twenty participants was 59.6 N (SD 13.2) and the mean endurance time was 86.7s (SD 34.9).

3.3 Discomfort Scores

Raw Discomfort Score (RDS) values, shown in Table 2, gave the lowest discomfort for the neutral wrist with neutral forearm at the frequency of 10 exertions/minute, with a mean value of 1.50 (SD 1.04). The increase in RDS for 20 exertions per minute, with a neutral wrist and neutral forearm, was only 13%. The highest discomfort at 10 exertions per minute was for 35%ROM ulnar wrist with 35%ROM wrist flexion and 60%ROM supine forearm. But for 20 exertions/minute the posture of highest discomfort (mean RDS 3.63 with SD=1.99) was at 60%ROM prone forearm with 35%ROM wrist flexion and 35%ROM radial wrist. This value was 2.14 times the RDS value for a neutral wrist with a neutral forearm at the same frequency.

[put Table 2 about here]

The SDS scores for the main experiment were not normally distributed (Levene's test: $p=0.001$) and a histogram of the RDS scores gave a distribution close to normal but a little skewed to the right. The $\mathrm{Log}_{10}(X+1)$ transformation of the RDS data achieved normality (Levene's test: $p>0.05$) and these data of Transformed Discomfort Score (TDS) were used for all statistical analyses. The average SDS values are show in Table 3.

(put Table 3 about here)

Mauchly's test was used in a repeated-measures ANCOVA with endurance time as the covariate. It showed that some of the interactions violated the sphericity requirement and on these the Greenhouse-Geisser correction was employed. Endurance time was not significant (p = 0.26) and so it could be excluded from further analysis. Then ANOVA was performed on the transformed data with Participants included as a random factor and using the five-way interaction as the Residual (Table 4). Forearm rotation, Wrist flexion/extension, Wrist deviation, Frequency, and Participant were all highly significant (p<0.001). The two-way interactions of Forearm rotation with Wrist deviation, and Forearm rotation with Participant, were also highly significant (p<0.001) while four higher order interactions were highly significant (p=0.001) or significant (p=0.01).

To investigate the effects of the different levels of independent variables on discomfort score, the Student Newman Keul's (SNK) test was performed on TDS values. Wrist radial deviation of 35%ROM was not significantly different from 35%ROM ulnar (p=0.914) but both were significantly different from neutral (p<0.05). Wrist extension of 35%ROM was not significantly different from neutral (p=0.103) and also not from 35%ROM wrist flexion (p=0.115). But 35%ROM wrist flexion was significantly different from neutral (p<0.05). Interestingly, 60%ROM prone was not significantly different from 60%ROM supine (p=0.623) but both were significantly different from the neutral forearm (p<0.05).

The experiment treatments were presented in blocks based on forearm rotation due to time delays and inconvenience to the participant changing that posture. Data from each of the blocks were compared using a one way ANOVA, and lack of a significant difference indicated there was not an order effect.

3.4 Forearm rotation

Both prone and supine rotations increased discomfort (Figure 4). For a neutral forearm rotation the difference between a frequency of 10/min and 20/min was 12% (t=3.865, p=0.001). This difference was greater for 60%ROM prone (14%; t=6.656, p<0.001) and 60%ROM supine (16%; t=7.031, p<0.001) forearm rotation.

[Put Figure 4 about here]

3.5 Wrist flexion/extension

The increase in discomfort between neutral and 35%ROM extension was slight (4%) at 10/min and not significant (t=1.699, p=0.106). But at 20/min it was 6% and significant (t=3.117, p=0.006) (see Figure 5). Differences in discomfort between the frequencies were approximately the same for all three levels of wrist flexion/extension, about 10-12%. The increase in discomfort for 35%ROM wrist flexion compared to neutral was 24% at 10/min and 11% at 20/min respectively.

[Put Figure 5 about here]

3.6 Wrist deviation

In general discomfort increased with wrist deviation in both radial and ulnar directions at 10/min and 20/min (Figure 6), but by little. For example, for 35%ROM ulnar deviation at 20 exertions/minute, the increase from neutral was about 6% (t=2.999, p=0.007). These differences were a lot more pronounced at the high combinations of the postures.

[Put Figure 6 about here]

3.7 Participants

To examine differences among Participants, the Endurance Time and Flexion MVC values were plotted in the increasing order of mean RDS (Figure 7) of the Participants. It can be seen that Endurance Time and Flexion MVC for most of the participants varied inversely with RDS (i.e. negative slopes) but R^2 values were very low (<0.1).

[put Figure 7 about here]

An SNK test on these data gave eleven groups with discomfort scores significantly different at $p < 0.05$. Participants 16 and 15 were each in separate groups with the lowest and second lowest TDS scores while Participants 12 and 11 were grouped together at the highest score. Most groups consisted of three to five Participants with some overlap between neighbouring groups. It was also noted that the 10N flexion force used for the experimental task ranged from about 12% of the flexion MVC (for participant no.7) to 26% (for participant no.4). It is notable that all the significant higher order interactions included Participants as one of the factors (Table 4).

3.8 Interaction of Forearm Rotation with Wrist Deviation

The TDS score increased with both supine and prone rotation compared to neutral, at neutral deviation and both 35%ROM radial and ulnar deviation (Figure 8). Discomfort at 60%ROM prone forearm, for both 35%ROM ulnar and radial wrist, was significantly higher than neutral ($t=4.16$ and $t=4.418$ $p<0.05$ respectively). Likewise, at 60%ROM supine rotation, for 35%ROM ulnar and radial deviation, discomfort scores were significantly higher than neutral (t=4.9 and t= 2.17 $p<0.05$ respectively). In particular, the increase at 35% ROM radial was greater than at neutral for both supine and prone rotations. However the differences in scores between the three levels of deviation were somewhat less than those due to rotation.

[put Figure 8 about here]

3.9 Interaction of Forearm Rotation with Participants

Its significance warranted further investigation. To investigate further simple main effects analysis was performed using one-way ANOVA for forearm rotation for each participant separately. The results showed that Forearm rotation was highly significant on TDS for most of the participants except for participants 1, 13, 15 and 17 (at p=0.067, 0.111, 0.377 and 0.691 respectively).

3.10 Body part discomfort map

After each block of the experiment participants were asked to mark the region of most discomfort among all the discomfort points. The cumulative responses are shown in Figure 8 which demonstrates that mostly discomfort was confined to the wrist and forearm, as intended in the configuration of the experiment. However discomfort reported in the forearm was slightly higher than wrist.

[put Figure 9 about here]

4. Discussion

4.1 Initial Experiment: Wrist flexion MVC

Generally the data showed that in non-neutral wrist/forearm postures MVC was lower than at neutral, as expected, because the muscle architecture is strongest in the mind range of movement. But, for 35% ROM wrist flexion and 60%ROM supine forearm combined with 35%ROM ulnar wrist, the MVC was greater than that obtained with a neutral wrist combined with 35%ROM flexion and 60%ROM supine forearm. Kattel. et al. (1996) reported higher grip strength for the wrist neutral, rather than flexed or in ulnar deviation. However, they did not study the effects of wrist extension and radial deviation. Sperling et al. (1993) stated that the optimal wrist position is at about 10^0 ulnar deviation with 30^0 extension and semi prone. The work reported here also indicated a larger flexion MVC for 60%ROM prone forearm compared to 60% supine.

The minimum mean wrist flexion MVC was recorded at 35%ROM radial wrist with 35% ROM flexion and 60%ROM prone forearm. That trend is similar to the findings of Carey (2001), where a 16% decrease in MVC was reported for 55%ROM wrist flexion combined with 55%ROM radial wrist for a fully prone forearm, relative to a neutral wrist for a fully prone forearm. Dempsey and Ayoub (1996) included wrist posture in their study of factors affecting pinch strength and they also reported lower values for flexion versus extension (4.2 versus 5.1 kg) and for radial deviation versus ulnar deviation (5.0 versus 5.1 kg). Their postures were also relative to the persons abilities, but at 100% ROM and not at intermediate levels across ROM.

4.2 Main Experiment: Endurance time

That this was not a significant covariate and this is against result reported in Mukhopadhyay et al. (2007b), where a similar test was significant ($p<0.001$). As in the work reported here, Mukhopadhyay et al. used an endurance task that closely mimicked their experimental task, but they used raw discomfort scores i.e. their scores were not standardised or transformed. But O'Sullivan and Gallwey (2005) used SDS scores and endurance time also failed to reach significance as a covariate. Maybe this is only effective if the raw scores are used as standardisation possibly removed the effect. However the graphical picture here suggests that it is relevant but perhaps nullified by the large variability of the data.

4.3 Discomfort

The significance of the main factors for wrist postures was in-line with the findings of Carey & Gallwey (2005). In addition, Wilhelm and Hallbeck (1997) reported higher torque strength for a neutral wrist compared to a deviated wrist. This supports the lower level of discomfort found in the present study for the neutral wrist and at 35% extension, compared to the 35 % flexion and both 35% ulnar and radial deviation. It has been shown that wrist flexion/extension and radial/ulnar deviation affect Carpal Tunnel Pressure (CTP) (Keir, 2007 and Smith et al., 1977). Hence, these findings on the wrist posture effects are in good concordance with other studies using objective data as the dependent variable.

Very low level of differences in the RDS values for 35% ROM in radial, ulnar and neutral wrist was noticed without forearm rotation for 10 exertions per minute. Also the discomfort was higher for 35% radial compared to 35% ulnar for 60% prone while it was visa versa for 60% supine rotation of forearm. Further analysis showed that these differences were not significantly different for supine rotation ($t=2.24$, $p=0.369$) but were significantly different for prone rotation (p<0.05). O'Sullivan & Gallwey (2002) and Mukhopadhyay et al. (2007a) obtained results that support the significant effect of Forearm rotation on discomfort score. The values could not be compared directly because the tasks were different in these two experiments. The mean values of the MVC flexion were less for prone and supine compared to a neutral forearm. This difference was about 16% less and 20% less for 60% ROM in prone and supine rotation respectively. This reduction in strength supports the finding of lower discomfort for a neutral forearm compared with prone/supine.

A laboratory experiment to compare conventional pliers with powered driver-fixture combinations (Li, 2003) also showed a significant reduction (<0.001) in EMG activity of the flexor digitorum superficialis muscle, and flexor carpi ulnaris muscle, of the right arm. This reduction was because the numbers of awkward wrist postures, including extension and ulnar deviation were significantly decreased when using the powered driver-fixture combinations. Pashoarelli et al. (2008) presented posture and discomfort data for various designs of ultrasound devices. Comparison of data from five device designs showed that the lowest discomfort and highest product acceptability ratings were for new device designs that involved more neutral wrist flexion/extension, wrist radial ulnar deviation and forearm rotation postures that two commercial products. Hence the findings of Li (2003) and Paschoarelli et al. (2008) support the present findings that discomfort increases wrist and forearm deviations from neutral.

Many products and tasks involve postures similar to those tested here and some have associations with injury or subjective reports of discomfort. For example, Mirka et al. (2002) found that a conventional spray gun design use involved up to 47^0 wrist flexion and up to 17^0 ulnar deviation. Computer input devices, especially the traditional mouse typically involves wrist extension and ulnar deviation with the forearm prone (Burgess-Limerick and Green, 2000). Toomings and Gavhed (2009) reported on the office ergonomics in sixteen Swedish call centres. Their data show that the wrists were extended between 15^0 and 30^0 during 32% of the observations, and between 15^0 and 30^0 ulnar deviation for 30% of the time. A survey of the participants indicated that 20% experienced prevalence of pain in the elbows/forearms/ wrists/hands/fingers during the previous week. The results from the present study would suggest that small amounts of wrist extension do not appear to result in a marked increase in discomfort, but ulnar deviation, even at low magnitudes such as 35% ROM does.

For the neutral postures, discomfort increased by 13% (1.5 to 1.7) when pace increased from 10 to 20 exertions per minute. But for the most difficult posture combination (60% prone, 35% flexion, 35% radial deviation) the increase was 36% (2.6 to 3.6). This most likely illustrates some of the significant interaction effects in the ANOVA which included Frequency. Carey and Gallwey (2002) also found frequency at the same levels as in this study to be significant when combined with wrist flexion and ulnar deviation.

4.4 Participants and its interactions

Although Participants was highly significant, the endurance time was not a significant covariate. A possible reason is the individual differences in the range of the perceived discomfort, since participant was significant in the SNK test. Chapparo et al. (1999) found that younger participants had higher discomfort in the hand and wrist only, while older participants reported higher discomfort in the hand, wrist and forearm in computer mouse

use. In the present study, participants aged less than 22 had a higher ROM for Forearm rotation and higher mean RDS compared to the older participants.

4.5 Discomfort Trends

To examine whether or not the changes in discomfort were additive, tests of parallelism were carried out on the data presented in Figures 6, 7 and 8. For Rotation, the slopes of the lines were not significantly different for supine rotation (t=2.24, p=0.369), which suggests parallelism, but they were significantly different for prone ($p<0.05$). For both wrist flexion and extension the slopes were not significantly different between the two frequencies (t=1.54, p=0.141; and t=1.17, p=0.258). For wrist deviation also, the slopes for the two frequencies were not significantly different (t=1.20, p=0.245; t=1.31, p=0.206). For the interaction of rotation with deviation the slopes were yet again not significantly different (prone: t=0.518, p=0.610; supine: t=1.484, p=0.154) hence the effect of wrist deviation was additive relative to neutral. To some extent it can be seen that an increase in severity seems to have added a constant amount to the level of discomfort. But with only three plotted points these data must be treated with some circumspection.

4.6 Study design and industrial relevance of treatments

4.6.1 Experiment Duration

This study was an experimental simulation of the elements of occupational tasks involving light force exertion such as screw driving, packaging, assembling etc. Generally in industry repetitive tasks are not performed for a duration of only five minutes. So there was a question as to how useful these results are for real tasks, which continue for longer durations such as 2 hours or 4 hours. But this was not the aim of the study. It was performed to investigate basic issues concerning the extent of discomfort increase with the increase in %ROM of combined wrist and forearm postures. Hence the present findings help to map the discomfort profile for such activities.

4.6.2 Recovery Time

Although participants could request recovery time between each part of experiment of more than one minute until they felt comfortable, they very rarely did so. It appears to be a very short time but other studies have used the same rest period for these kinds of tasks in simulated experiments (Mogk and Keir, 2003; Carey and Gallwey, 2002). Carey (2001) reported that there was very little or no accumulation of discomfort at the end of a one-minute rest period. As a follow-up in the present study, the data were tested for a possible order effect by breaking it into three parts but it was not significant. This implies that the one-minute recovery period was sufficient to avoid an accumulation of discomfort on this task.

4.6.3 Ranges of Motion

Ranges of motions measured in this experiment were lower (in degree terms) than the findings reported by other researchers (Table 6). This difference was greater for supine and prone rotation. One reason might be that ROM was recorded using electro-goniometers that were attached over the forearm. It was noted that, with rotation of the forearm, there was a small degree of slippage by the goniometer since it was attached to the skin, which did not rotate as completely as the movement of the forearm bones.

[put Table 5 about here]

The different ROM values can be explained from the findings of Marshall et al. (1999). In their study they did 48 pair-wise t-test comparisons for wrist and forearm rotations, and only six indicated no significant difference between the manual method of measurement and the reading from the electrogoniometer ($p<0.05$). Buchholz and Wellman (1997) investigated the effects of forearm rotation on the performance of the Penny & Giles electrogoniometer and found similar results. As per Gajdosik and Bohannon (1987) muscle length can also affect goniometer recordings. They concluded that the objective interpretation of the meaning of ROM measurements in light of the purposes and the limitations of goniometry should be encouraged.

4.6.4 Gender effect

The present study was limited to male participants only and there might be different effect if the results were applied to female workers. Treaster and Burr (2004) found that women have a significantly higher prevalence for many types of upper extremity WMSDs, even after controlling for the type of data source and confounders such as age or work factors. With men as the referent, the Odds Ratio (OR) or Prevalence Ratio (PR) for upper limb WMSD ranged from 0.85 to 10.05 for self-reports. For self-report combined with physical examination, the OR/PR ranged from 0.66 to 11.4. Hence, if the present results were applied to the female population there might well be a high prevalence of WMSDs.

Gun (1990) found that the RSI incidence rates varied widely between different occupations and industries, and suggested that the gender difference is largely due to the different job tasks assigned to women and men, rather than to any biological difference. Furthermore, when women and men perform the same task, women may be at higher risk of WMSD because of a mismatch between the workplace and their anthropometric dimensions. Also, when performing the same job, women were reported to be at a higher risk of WMDS (Silverstein, et al., 1986 and Armstrong et al., 1987). In other words, there is a real gender difference in WMSD risk that cannot be explained solely on the basis of differences in job factors. Independent exposure analysis should be done separately for men and women in order to be sensitive to gender related differences in anthropometry and work techniques.

5. Conclusions

- Forearm rotation had a highly significant at $p<0.001$ on discomfort for repetitive wrist flexion task. With the forearm at 60% ROM prone and 60% ROM supine, the cumulative means of the SDS scoures were 85% and 90% more compared to neutral wrist.
- Deviation of the wrist in the vertical plane (flexion/extension) had a significant effect on discomfort ($p=0.001$). Post hoc tests revealed that the values for 35%ROM wrist extension was not significantly different from neutral ($p=0.103$). There was an increase in average cumulative SDS of 28% for 35%ROM wrist flexion compared to neutral.
- Wrist radial/ulnar deviation had a highly significant effect ($p<0.001$) on SDS with an increase of 22% and 21% for 35%ROM radial and ulnar deviation respectively.
- Frequency was also highly significant ($p<0.001$) with an increase of 28% for 20 exertions/minute compared to 10 exertions/minute for 10N wrist flexion repetitive exertions.

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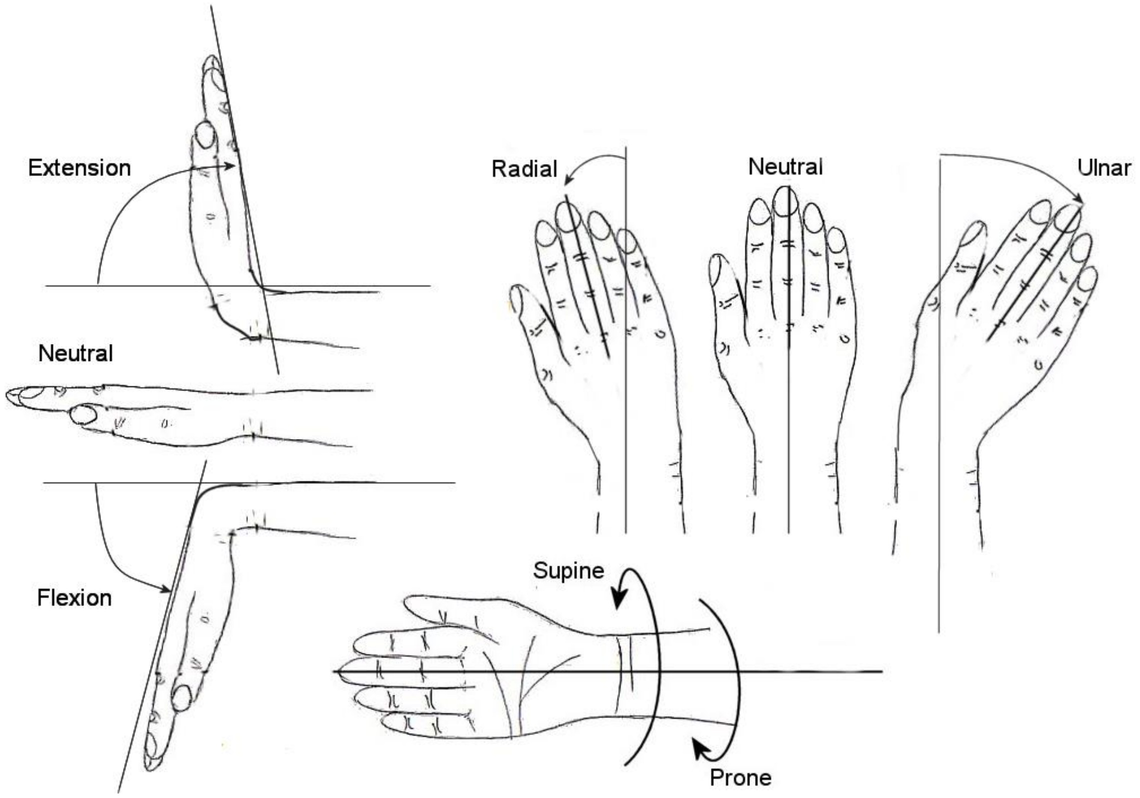


Figure 1 The postures used as independent variables for the experimental task

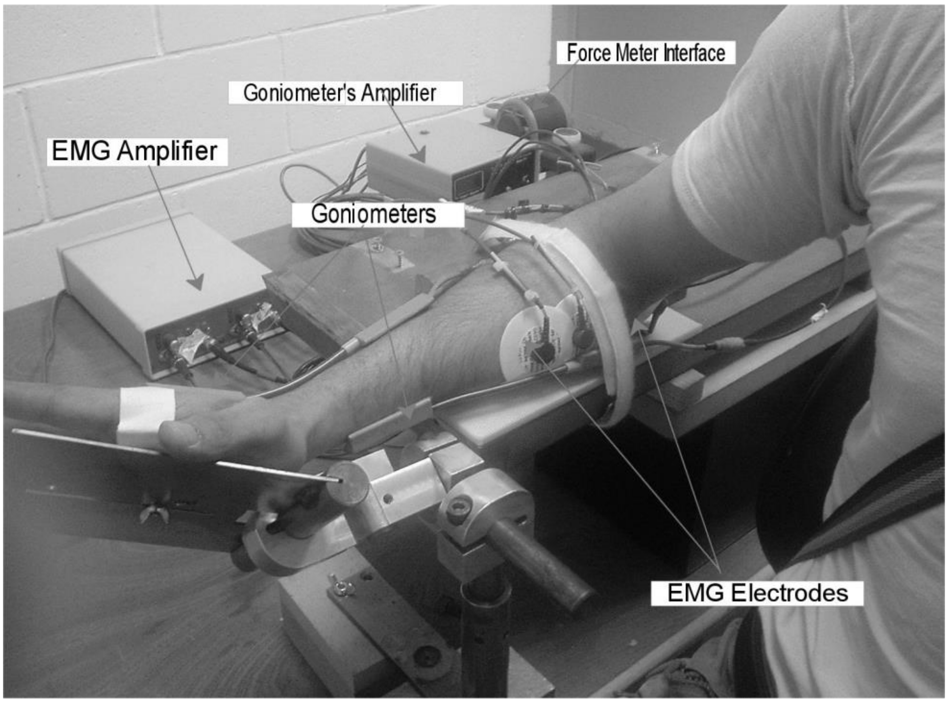
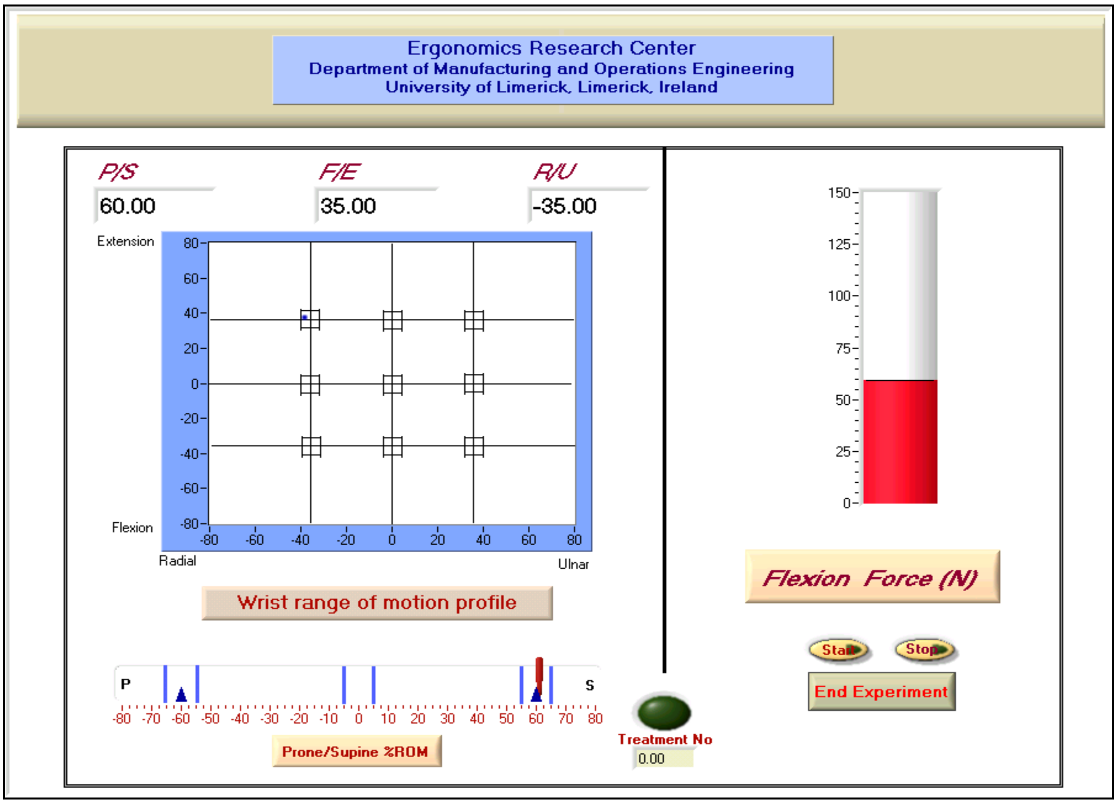


Figure 2 Experimental Rig



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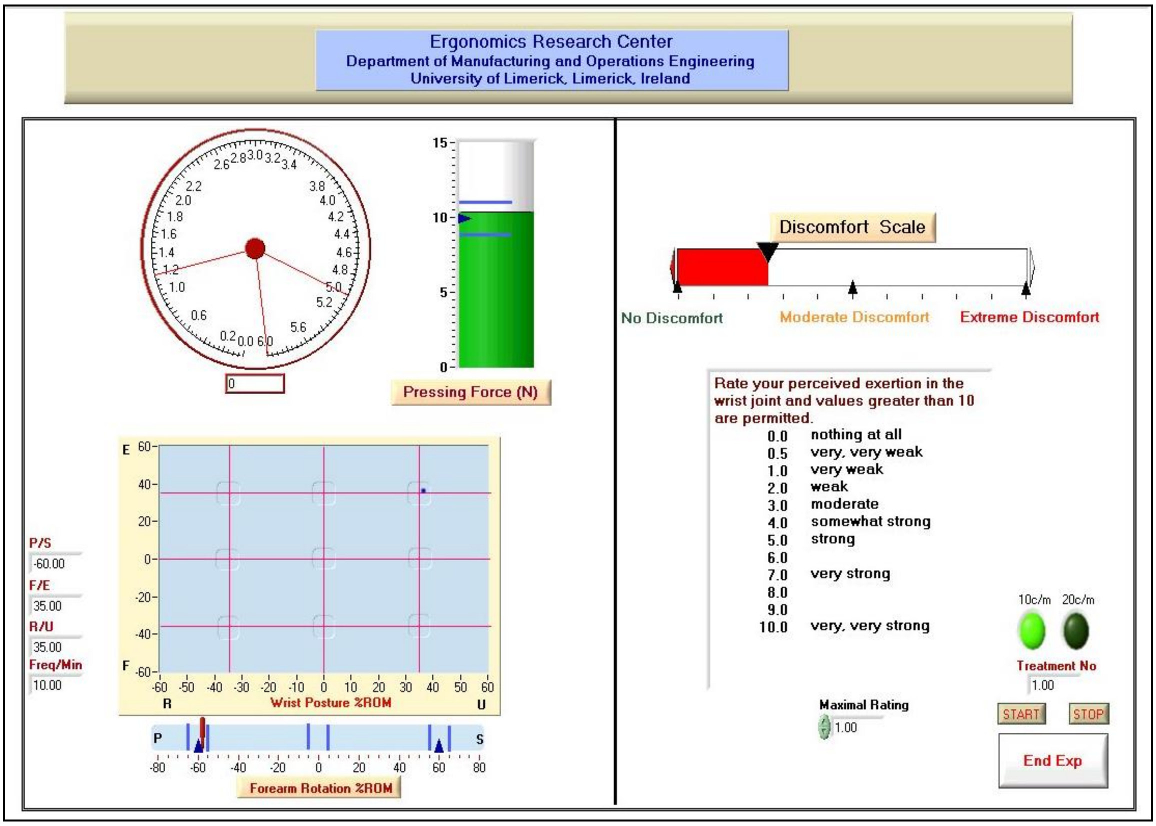
F/E 35.00
R/U -35.00
Treatment No 0.00

Figure 3 Screen Shot of LABVIEW6i VI for recording of wrist flexion MVC



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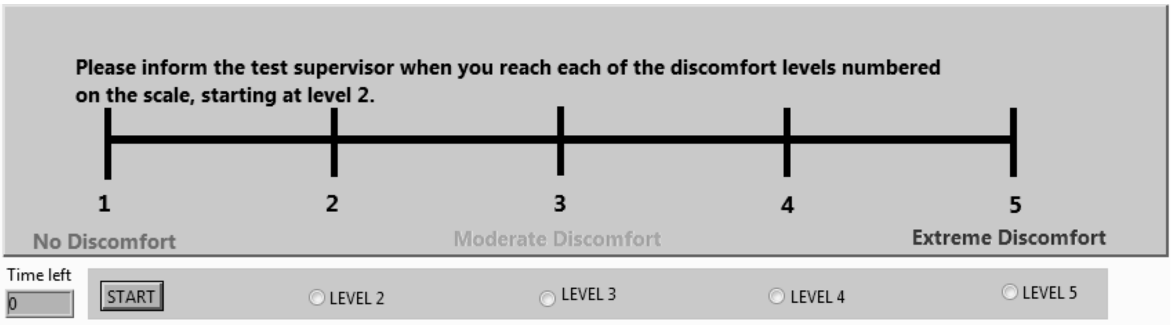
Rate your perceived exertion in the wrist joint and values greater than 10 are permitted.

0.0	nothing at all
0.5	very, very weak
1.0	very weak
2.0	weak
3.0	moderate
4.0	somewhat strong
5.0	strong
6.0	
7.0	very strong
8.0	
9.0	
10.0	very, very strong

Maximal Rating 1.00
Treatment No 1.00

Figure 4 Screen shot of LABVIEW6i VI for recording discomfort score



Please inform the test supervisor when you reach each of the discomfort levels numbered on the scale, starting at level 2.

Time left: 0

Figure 5 Scale used for recording endurance time

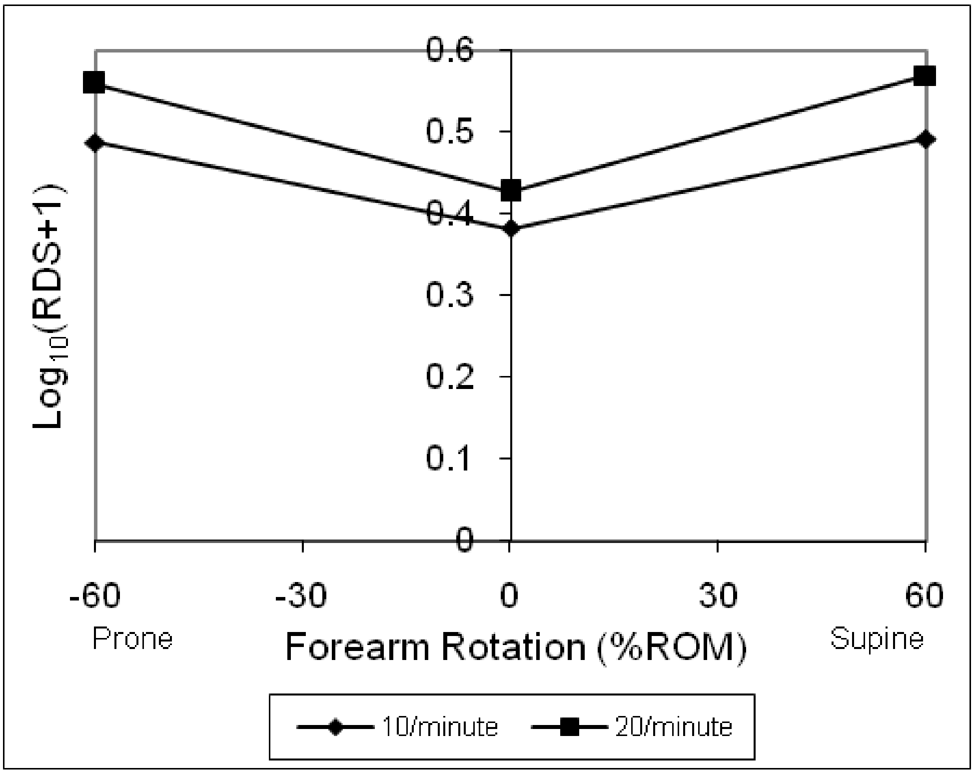


Figure 6 TDS for forearm rotation by frequency

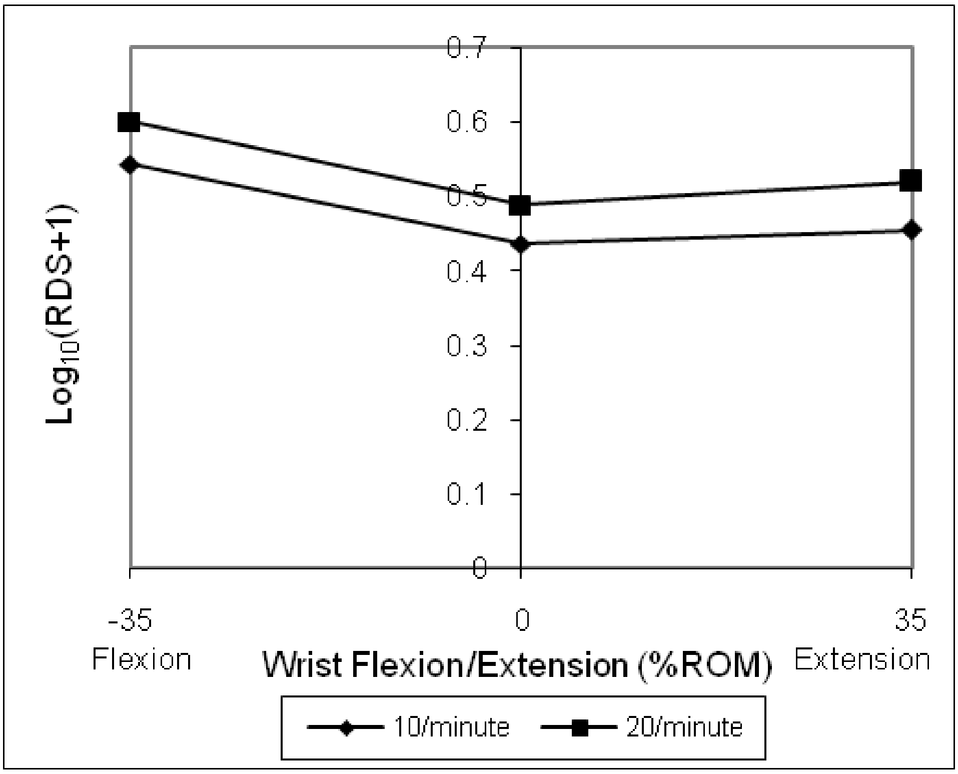


Figure 7 TDS for flexion/extension by frequency

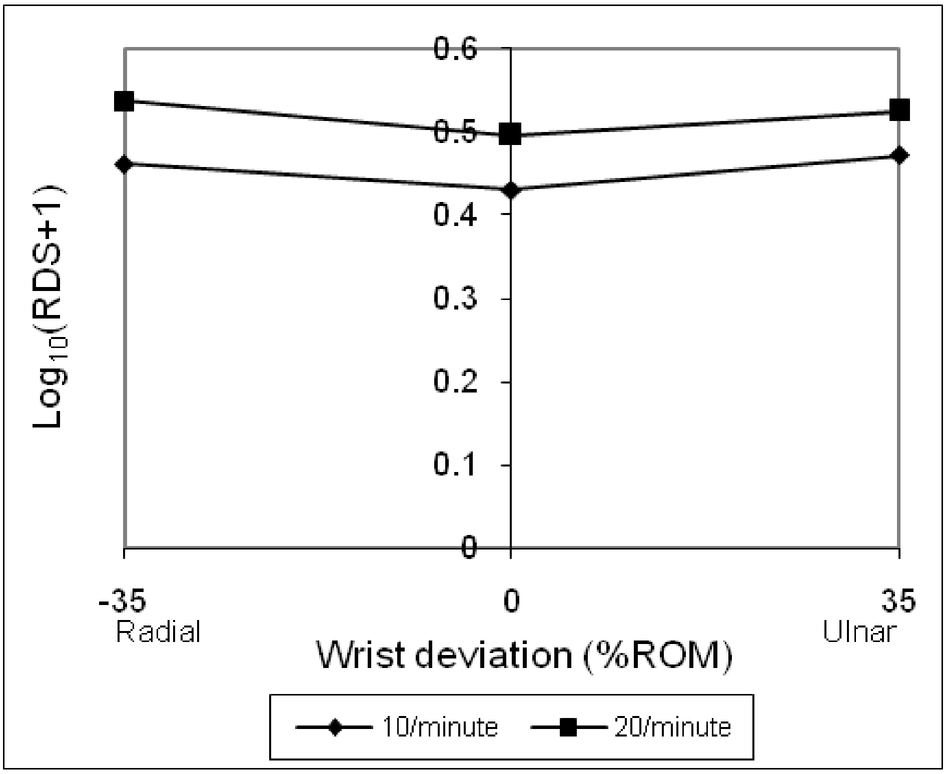


Figure 8 TDS for deviation by frequency

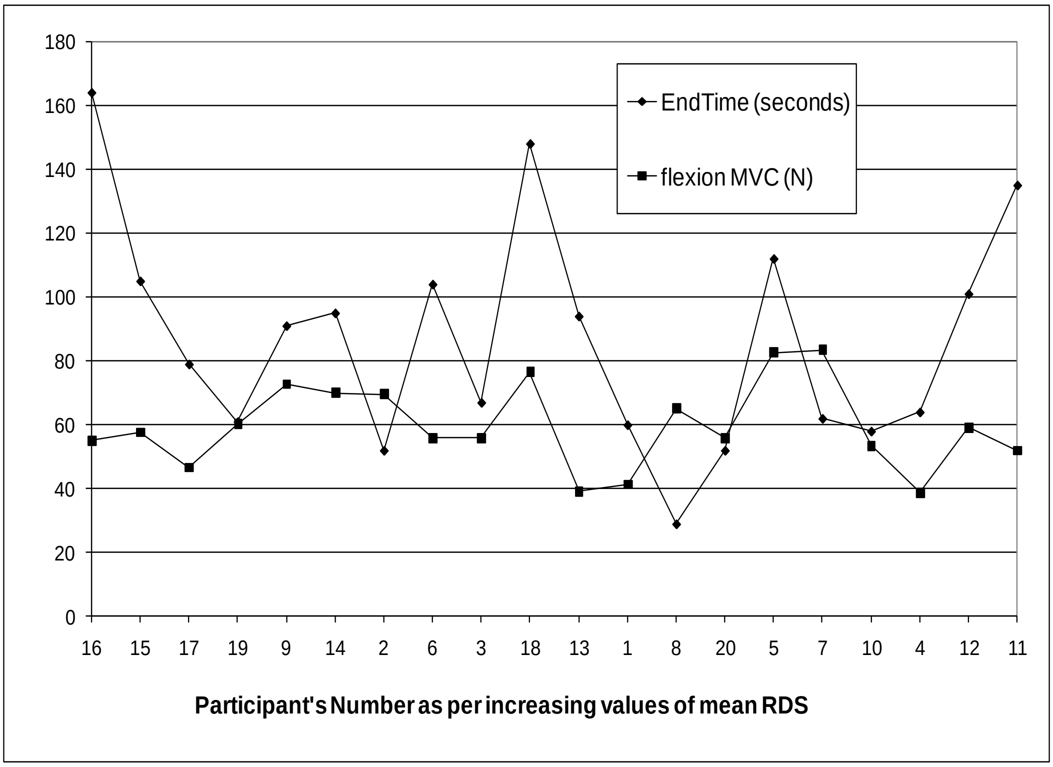


Figure 9 Endurance time and flexion MVC vs. Participant in increasing order of RDS

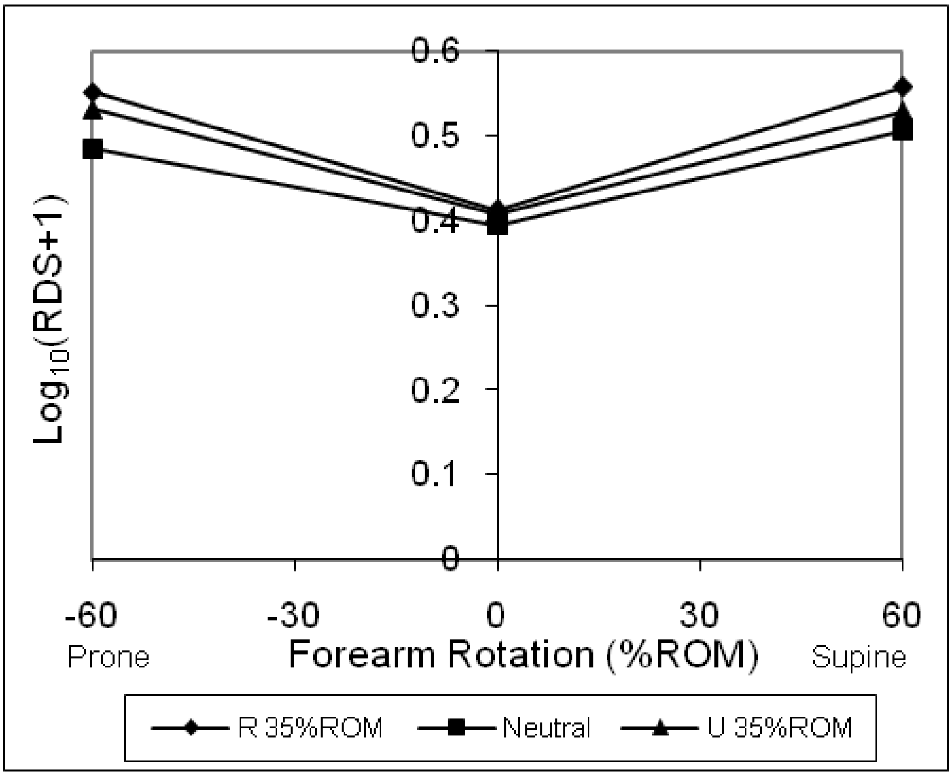


Figure 10 TDS vs. rotation by deviation

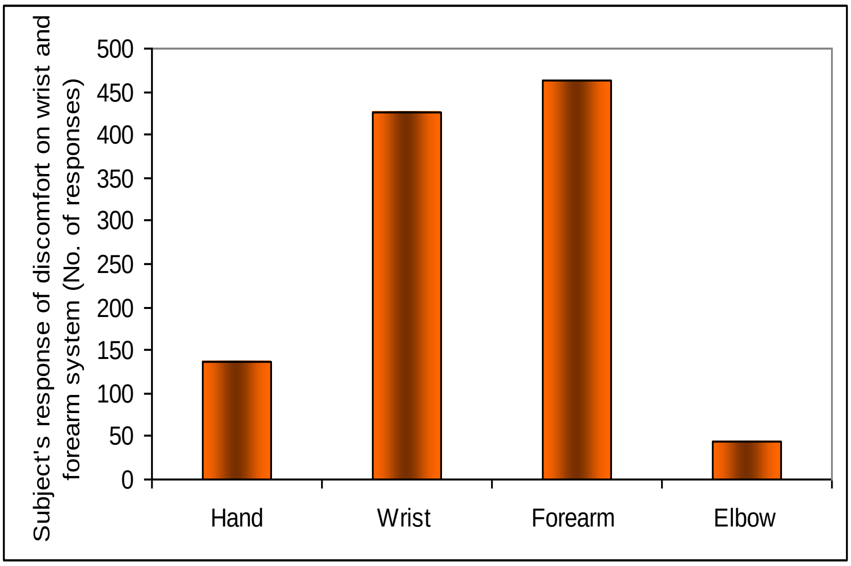


Figure 11 The response of discomfort on body parts map of the wrist and forearm system

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Table 1 Wrist flexion MVC (N) for posture combinations

		Forearm Rotation			**Mean (SD)**
		Prone 60%ROM	Neutral	Supine 60%ROM	
Wrist Flexion / Extension↓	Wrist deviation↓	Mean (SD)	Mean (SD)	Mean (SD)	
35% ROM Flexion	Radial 35% ROM	53.83 (22.77)	66.98 (22.75)	59.55 (24.04)	63.03 (22.4)
	Neutral	59.05 (25.27)	74.51 (27.29)	60.80 (25.43)	
	Ulnar 35% ROM	58.29 (22.71)	71.83 (27.69)	62.45 (20.70)	
Neutral	Radial 35% ROM	59.27 (27.09)	78.81 (32.99)	55.18 (24.94)	69.01 (25.5)
	Neutral	66.75 (27.68)	83.80 (33.26)	66.78 (22.92)	
	Ulnar 35% ROM	66.32 (24.95)	83.27 (29.64)	60.92 (18.21)	
35% ROM Extension	Radial 35% ROM	62.65 (17.46)	67.62 (25.36)	54.43 (19.92)	64.21 (19.9)
	Neutral	69.39 (20.79)	71.82 (25.75)	61.10 (21.06)	
	Ulnar 35% ROM	63.10 (19.59)	71.41 (25.19)	56.39 (20.84)	
	Mean (SD)	62.07 (21.8)	74.45 (26.5)	59.73 (iff)	
		Wrist deviation			
		R 35% ROM	Neutral	U 35% ROM	
	Mean (SD)	62.04 (22.1)	68.22 (24.4)	66.00 (21.8)	

Table 2 Raw Discomfort Scores for posture combinations (neutral posture values in bold)

		Forearm rotation					
		10 exertions/minute			20 exertions/minute		
		Prone 60%ROM	Neutral	Supine 60%ROM	Prone 60%ROM	Neutral	Supine 60%ROM
Wrist flexion / extension (ROM)↓	Wrist deviation (ROM)↓	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
35% ROM Flexion	Radial 35% ROM	2.66 (1.44)	1.71 (1.40)	2.65 (1.89)	3.63 (1.99)	2.11 (1.62)	3.49 (1.87)
	Neutral	2.22 (1.37)	1.71 (1.18)	2.59 (1.58)	2.96 (1.68)	2.11 (1.48)	3.20 (1.75)
	Ulnar 35% ROM	2.53 (1.58)	1.79 (1.31)	2.99 (1.72)	3.51 (1.78)	2.17 (1.45)	3.37 (1.88)
Neutral	Radial 35% ROM	2.66 (2.27)	1.52 (1.07)	2.30 (1.46)	3.06 (2.08)	1.92 (1.20)	3.01 (1.40)
	Neutral	1.93 (1.49)	**1.50 (1.04)**	2.04 (1.32)	2.35 (1.75)	**1.70 (1.20)**	2.59 (1.64)
	Ulnar 35% ROM	2.23 (1.58)	1.82 (1.24)	2.38 (1.60)	2.55 (1.87)	1.82 (1.30)	2.98 (1.86)
35% ROM Extension	Radial 35% ROM	2.71 (2.71)	1.55 (1.08)	2.55 (1.71)	3.35 (1.66)	1.86 (1.27)	3.19 (1.93)
	Neutral	2.32 (1.44)	1.48 (0.97)	1.87 (1.20)	2.85 (1.59)	1.85 (1.19)	2.64 (1.46)
	Ulnar 35% ROM	2.54 (1.72)	1.76 (1.17)	2.70 (1.60)	3.03 (1.97)	2.15 (1.38)	3.24 (1.69)

Table 3 Standardised Discomfort Scores for posture combinations

		Forearm rotation					
		10 exertions/minute			20 exertions/minute		
		Prone 60%ROM	Neutral	Supine 60%ROM	Prone 60%ROM	Neutral	Supine 60%ROM
Wrist Flexion / Extension (ROM)↓	Wrist deviation (ROM)↓	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
35% ROM Flexion	Radial 35% ROM	4.59 (1.83)	2.14 (1.71)	4.27 (2.72)	6.70 (2.28)	3.09 (2.03)	6.64 (2.51)
	Neutral	3.50 (1.86)	2.30 (1.82)	4.36 (2.46)	5.35 (2.74)	3.21 (2.15)	5.80 (2.23)
	Ulnar 35% ROM	4.16 (2.18)	2.42 (1.99)	5.53 (2.66)	6.46 (2.38)	3.37 (2.04)	6.30 (2.98)
Neutral	Radial 35% ROM	4.12 (2.80)	1.81 (1.35)	3.62 (2.15)	5.24 (2.41)	2.78 (1.50)	5.56 (2.24)
	Neutral	2.72 (2.00)	1.69 (1.87)	3.04 (1.99)	3.76 (2.39)	2.23 (1.93)	4.24 (2.15)
	Ulnar 35% ROM	3.40 (2.16)	2.59 (2.42)	3.72 (2.30)	4.33 (2.68)	2.58 (1.68)	5.36 (2.99)
35% ROM Extension	Radial 35% ROM	4.84 (2.15)	1.93 (1.44)	3.92 (2.46)	6.20 (2.25)	2.63 (1.37)	5.74 (2.58)
	Neutral	3.55 (2.08)	1.77 (1.65)	2.55 (2.19)	4.88 (2.34)	2.69 (2.24)	4.54 (2.17)
	Ulnar 35% ROM	4.15 (2.14)	2.43 (2.07)	4.34 (2.48)	5.32 (2.66)	3.26 (2.00)	5.76 (2.18)

Table 4 ANOVA Table for TDS values

Source	Type III Sum of Squares	df	Mean Square	F	Sig. (p-value)
Forearm Rotation (PS)	3.586	2	1.793	17.764	0.001
Wrist Flex./Ext. (FE)	0.422	2	0.211	8.785	0.001
Wrist Deviation (RU)	0.311	2	0.155	14.916	0.001
Frequency (FR)	1.124	1	1.124	73.829	0.001
Participant	29.968	19	1.577	13.742	0.001
PS * FE	0.106	4	0.026	1.519	0.205
PS * RU	0.177	4	0.044	4.911	0.001
FE * RU	0.030	4	0.007	0.928	0.452
PS * FE * RU	0.051	8	0.006	0.646	0.738
PS * FR	0.052	2	0.026	2.934	0.065
FE * FR	0.028	2	0.014	1.907	0.162
PS * FE * FR	0.032	4	0.008	1.654	0.169
RU * FR	0.024	2	0.012	3.161	0.054
PS * RU * FR	0.009	4	0.002	0.476	0.753
FE * RU * FR	0.015	4	0.004	1.172	0.330
PS * FE * RU * FR	0.035	8	0.004	1.034	0.413
PS * Participant	3.836	38	0.101	5.075	0.001
FE * Participant	0.912	38	0.024	1.266	0.218
PS * FE * Participant	1.324	76	0.017	1.655	0.009
RU * Participant	0.396	38	0.010	1.493	0.213
PS * RU * Participant	0.684	76	0.009	0.850	0.771
FE * RU * Participant	0.608	76	0.008	0.896	0.688
PS * FE * RU * Participant	1.495	152	0.010	2.344	0.001
FR * Participant	0.289	19	0.015	1.358	0.231
PS * FR * Participant	0.340	38	0.009	2.132	0.001
FE * FR * Participant	0.279	38	0.007	1.750	0.010
PS * FE * FR * Participant	0.371	76	0.005	1.163	0.213
RU * FR * Participant	0.147	38	0.004	0.922	0.603
PS * RU * FR * Participant	0.376	76	0.005	1.179	0.196
FE * RU * FR * Participant	0.250	76	0.003	0.786	0.880
PS * FE * RU * FR * Participant (Residual)	0.638	152	0.004	.	.
Total	47.916	1079			

Table 5 Mean ROM values of wrist/forearm deviations (degrees) from the present and other studies

Study	**Wrist Flexion**	**Wrist Extension**	**Radial Deviation**	**Ulnar Deviation**	**Prone Rotation**	**Supine Rotation**
Present Study	71^0	56^0	16^0	51^0	45^0	48^0
Kee & Karwowski (2001b)	72^0	65^0	29^0	50^0	87^0	119^0
Donna et al. (1979)	76.4^0	74.9^0	21.5^0	36.0^0	75.8^0	82.1^0
Amer. Acad. of Orthop. Surg. (1965)	73^0	71^0	19^0	33^0	71^0	84^0